ABSTRACT

The flow-reversal elliptical cylindrical end chamber mufflers of short length are used often in the modern day automotive exhaust systems. The conventional 1-D axial plane wave theory is not able to predict their acoustical attenuation performance in view of the fact that the chamber length is not enough for the evanescent 3-D modes generated at the junctions to decay sufficiently for frequencies below the cut-off frequency. Also, due to the large area expansion ratio at the inlet, the first few higher order modes get cut on even in the low frequency regime. This necessitates a 3-D FEM or 3-D BEM analysis, which is cumbersome and time consuming. Therefore, an ingenious 1-D transverse plane wave theory is developed by considering plane wave propagation along the major-axis of the elliptical section, whereby a 2-port axially short elliptical and circular chamber muffler is characterized by means of the transfer matrix [**T**] or impedance matrix [**Z**]. Two different approaches are followed: (1) a numerical scheme such as the Matrizant approach, and (2) an analytical approach based upon the Frobenius series solution of the Webster's equation governing the transverse plane wave propagation. The convective effects of mean flow are neglected; however the dissipative effects at the ports are taken into account. The TL predicted by this 1-D transverse plane wave analysis is compared with that obtained by means of the 3-D analytical approach and numerical (FEM/BEM) methods. An excellent agreement is observed between this simplified 1-D approach and the 3-D approaches at least up to the cut-on frequency of the (1, 1) even mode in the case of elliptical cylindrical chambers, or the (1, 0) mode in the case of circular cylindrical chambers, thereby validating this 1-D transverse plane wave theory. The acoustical attenuation characteristics of such short chamber mufflers for various configurations are discussed, qualitatively as well as quantitatively. Moreover, the Frobenius series solution enables one to obtain non-dimensional frequencies for determining the resonance peak and trough in the TL graph. The use of this theory is, however, limited to configurations in which both the ports are located along the major axis in the case of elliptical chambers and along the same diameter for circular chambers.

The method of cascading the [**T**] matrices of the 2-port elements cannot be used to analyze a network arrangement of 2-port elements owing to the non-unique direction of wave propagation in such a network of acoustic elements. Although, a few papers are found in the literature reporting the analysis of a network of 2-port acoustic elements, no work is seen on the analysis of a network of multi-port elements having more than two external ports. Therefore, a generalized algorithm is proposed for analyzing a general network arrangement of linear multi-port acoustic elements having N inlet ports and M outlet ports. Each of these multi-port elements constituting the network may be interconnected to each other in an arbitrary manner. By appropriate book-keeping of the equations obtained by the [**Z**] matrix characterizing each of the multi-port and 2-port elements along with the junction laws (which imply the equality of acoustic pressure and conservativeness of mass velocity at a multi-port junction), an overall connectivity matrix is obtained, whereupon a global [**Z**] matrix is obtained which characterizes the entire network. Generalized expressions are derived for the evaluation of acoustic performance evaluation parameters such as transmission loss (TL) and insertion loss (IL) for a multiple inlet and multiple outlet (MIMO) system. Some of the characteristic properties of a general multi-port element are also studied in this chapter. The 1-D axial and transverse plane wave analysis is used to characterize axially long and short chambers, respectively, in terms of the [**Z**] matrix. Different network arrangements of multi-port elements are constructed, wherein the TL performance of such MIMO networks obtained on the basis of either the 1-D axial or 1-D transverse plane wave theory are compared with 3-D FEA carried on a commercial software. The versatility of this algorithm is that it can deal with more than two external or terminal ports, i.e., one can have multiple inlets and outlets in a complicated acoustic network.

A generalized approach/algorithm is presented to characterize rigid wall reactive multi-port chamber mufflers of different geometries by means of a 3-D analytical formulation based upon the modal expansion and the uniform piston-driven model. The geometries analyzed here are rectangular plenum chambers, circular cylindrical chamber mufflers with and without a pass tube, elliptical cylindrical chamber mufflers, spherical and hemispherical chambers, conical chamber mufflers with and without a co-axial pass tube and sectoral cylindrical chamber mufflers of circular and elliptical cross-section as well as sectoral conical chamber mufflers. Computer codes or subroutines have been developed wherein by choosing appropriate mode functions in the generalized pressure response function, one can characterize a multi-port chamber muffler of any of the aforementioned separable geometrical shapes in terms of the [**Z**] matrix, subsequent to which the TL performance of these chambers is evaluated in terms of the scattering matrix [**S**] parameters by making use of the relations between [**Z**] and [**S**] matrices derived earlier. Interestingly, the [**Z**] matrix approach combined with the uniform piston-driven model is indeed ideally suited for the 3-D analytical formulation inasmuch as regardless of the number of ports, one deals with only one area discontinuity at a time, thereby making the analysis convenient for a multi-port muffler configuration with arbitrary location of ports.

The TL characteristics of SISO chambers corresponding to each of the aforementioned geometries (especially the elliptical cylindrical chamber) are analyzed in detail with respect to the effect of chamber dimensions (chamber length and transverse dimensions), and relative angular and axial location of ports. Furthermore, the analysis of SIDO (i.e., single inlet and double outlet) chamber mufflers is given special consideration. In particular, we examine

(1) the effect of additional outlet port (second outlet port),

(2) variation in the relative angular or axial location of the additional or second outlet port (keeping the location of the inlet port and the outlet ports of the original SISO chamber to be constant) and

(3) the effect of interchanging the location of the inlet and outlet ports

on the TL performance of these mufflers. Thus, design guidelines are developed for the optimal location of the inlet and outlet ports keeping in mind the broadband attenuation characteristics for a single inlet and multiple outlet (SIMO) system.

The non-dimensional limits up to which a flow-reversal elliptical (or circular) cylindrical end chamber having an end-inlet and end-outlet configuration is acoustically short (so that the 1-D transverse plane wave theory is applicable) and the limits beyond which it is acoustically long (so that the 1-D axial plane wave theory is applicable) is determined in terms of the L/D_1 ratio or equivalently, in terms of the L/d_0 ratio. Towards this end, two different configurations of the elliptical cylindrical chamber are considered, namely,

(1) End-Offset Inlet (located along the major-axis of the ellipse) and End-Centered Outlet

(2) End-Offset Inlet and End-Offset Outlet (both the ports located on the major-axis of the ellipse and at equal offset distance from the center).

The former configuration is analyzed using 3-D FEA simulations (on SYSNOISE) while the 3-D analytical uniform piston-driven model is used to analyze the latter configuration. The existence of the higher order evanescent modes in the axially long reversal chamber at low frequency (before the cut-on frequency of the (1, 1) even mode or (1, 0) mode) causes a shift in the resonance peak predicted by the 1-D axial plane wave theory and 3-D analytical approach. Thus, the 1-D axial plane wave analysis is corrected by introducing appropriate end correction due to the modified or effective length of the elliptical cylindrical chamber. An empirical formulae has been developed to obtain the average non-dimensional end correction (δ) for the aforementioned configurations as functions of the expansion ratio, (i.e., D_1/d_0), minor-axis to major-axis ratio, (i.e., D_2/D_1) and the center-offset distance ratio, (i.e., c/d_0). The intermediate limits between which the chamber is neither short nor long (acoustically) has also been obtained. Furthermore, an ingenious method (Quasi 1-D approach) of combining the 1-D transverse plane wave model with the 1-D axial plane wave model using the [**Z**] matrix is also proposed for the end-offset inlet and end-centered outlet configuration. A 3-D analytical procedure has also been developed which also enables one to determine the end-correction in axially long 2-port flow-reversal end chamber mufflers for different geometries such as rectangular, circular and elliptical cylindrical as well as conical chambers, a priori to the computation of TL. Using this novel analytical technique, we determine the end correction for arbitrary locations on the two end ports on the end face of an axially long flow-reversal end chamber. The applicability of this method is also demonstrated for determination of the end corrections for the 2-port circular cylindrical chamber configuration without and with a pass tube, elliptical cylindrical chambers as well as rectangular and conical chambers.